CP VIOLATION IN B HADRONS AT THE TEVATRON

L.B. OAKES
for the CDF and DØ collaborations
Department of Physics, Subdepartment of Particle Physics, Denys Wilkinson Building, 1 Keble Road, Oxford OX1 3NP, England

The latest results are presented from DØ and CDF on CP violation in the B_s^0 system, including measurements of the CP violating phase $\beta_s^{J/\psi\phi}$, B_s^0 lifetime, τ_s, and width difference, $\Delta\Gamma_s$ using $2.8fb^{-1}$ integrated luminosity. In addition to results from the individual experiments, the Tevatron combined result for $\beta_s^{J/\psi\phi}$ is shown. The improvements made to the analyses for upcoming results from both experiments are also introduced.

1 Introduction

The study of neutral B meson properties can provide important tests of the Standard Model (SM) including constraints on parameters of the CKM matrix. While the B^0 system has been thoroughly investigated by B factories, precision measurements in the B_s^0 system are a more recent development, driven largely by the Tevatron experiments. The $B_s^0 - \bar{B}_s^0$ system has the potential to yield indirect observations of New Physics (NP), through the presence of non-SM particles in second order weak interaction processes such as neutral B meson mixing. Both the CDF and DØ experiments at the Fermilab Tevatron have published measurements of the B_s mixing frequency, Δm_s, but in order to constrain potential NP contributions in this system it is also necessary to precisely measure the CP violating phase, β_s. At the Tevatron, the golden mode for this measurement is $B_s^0 \to J/\psi\phi$. The $J/\psi\phi$ final state is common to B_s^0 and $\bar{B}_s^0$ decays; CP violation occurs in this channel through interference between decays with and without B_s^0 mixing. The phase, β_s, between these two decays is predicted to be close to zero in the SM, so a significant excess would be a clear indication of evidence for NP in this channel.

2 Neutral B_s^0 system phenomenology

The flavour eigenstates of B_s^0 mesons in the SM are not the same as the mass eigenstates, leading to oscillations between $|B_s^0\rangle = (\bar{b}s)$ and $|\bar{B}_s^0\rangle = (b\bar{s})$ via the second order weak interactions. The phenomenology of this weak mixing is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The time evolution of the $B_s^0 - \bar{B}_s^0$ system is governed by the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \mathcal{H}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \equiv \left[\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}\right]\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \qquad (1)$$

where the M and Γ matrices describe the mass and decays of the system. The mass eigenstates can be obtained by diagonalising $\mathcal{H}$; $|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$ and $|B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ where

$|q/p| = 1$ in the case of no direct CP violation, as predicted in the $J/\psi\phi$ channel, and the indices H and L label the heavy and light eigenstates respectively. The mass difference, Δm_s, between the heavy and light states is proportional to the frequency of B_s^0 mixing and is approximately equal to $2|M_{12}|$. The mass eigenstates have a small but non negligible lifetime difference, which can be described in terms of the decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(2\phi_s)$ where the CP violating phase is defined as $\phi_s = arg(-M_{12}/\Gamma_{12})$ and the mean decay width $\Gamma_s = 1/\tau_s$. The SM predicts ϕ_s^{SM} to be of order 0.004, and it would be expected to increase in the presence of NP. The mixing frequency, Δm_s has been well determined by Tevatron measurements, CDF published a 5σ observation of mixing with $\Delta m_s = 17.77 \pm 0.10$ (stat.) $\pm$ 0.07 (syst.)ps^{-1} and DØ 3σ evidence with $\Delta m_s = 18.52 \pm 0.91\text{ps}^{-1}$.

3 *CP* violation in $B_s \to J/\psi\phi$

The relative phase, β_s, between decays of a B_s^0 meson to $J/\psi\phi$ directly, and after mixing to $\bar{B}_s^0$, is defined in the SM as

$$\beta_s^{SM} = arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \approx 0.04 \tag{2}$$

A New Physics phase, contributing to the weak mixing diagrams in the neutral B_s^0 system would introduce a new physics phase ϕ_s^{NP} to β_s such that the measured value would be $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$. The same NP phase would enhance ϕ_s, giving $\phi_s = \phi_s^{SM} + \phi_s^{NP}$. As both β_s^{SM} and ϕ_s^{SM} are predicted to be close to zero, the NP phase would dominate, and the measured phase would be $2\beta_s \approx -\phi_s \approx \phi_s^{NP}$.

The decay $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ is fully reconstructed from events which pass the di-muon trigger. The final state is an admixture of CP odd and even states, which can be separated according to their angular momentum. The total angular momentum of the $J/\psi\phi$ state can be $L = 0$, 1, or 2, and the CP of the state is $(-1)^L$, so the $L = 0, 2$ states are CP even, and the $L = 1$ state is CP odd. These CP states can be separated using the angular distribution of the four final state particles, the muons and kaons from the decay of the J/ψ and ϕ. Both CDF and DØ use the transversity basis [1] to define the angular dependence of the final state, where the relative directions of the four particles can be described in terms of three transversity angles, $\{\cos\theta_T, \phi_T, \cos\psi_T\}$ which are defined by the direction of the decaying J/ψ and ϕ mesons. In the transversity basis, the decay amplitude can be separated into three components which represent different linear polarisation states.

The angular analysis is combined with time development and mass dependence in a multivariate likelihood fit. In the simplest case, the fit without flavour tagging information, the likelihood function has a four fold ambiguity under the transformations $\{\beta_s, \Delta\Gamma, \phi_\parallel, \phi_\perp\} \Leftrightarrow \{\phi/2 - \beta_s, -\Delta\Gamma, 2\pi - \phi_\parallel, \pi - \phi_\perp\}$ and $\beta_s \Leftrightarrow -\beta_s$, where the strong phases are defined in terms of the transversity amplitudes, $\phi_\parallel \equiv arg(A_\parallel^* A_0)$ and $\phi_\perp \equiv arg(A_\perp^* A_0)$. By flavour tagging the initial B_s^0 meson, the time development of B_s^0 and $\bar{B}_s^0$ states can be followed separately, which removes the insensitivity to the sign of β_s and $\Delta\Gamma$. This reduces the ambiguity to two points. The flavour of the decaying B meson is tagged using a combination of opposite side (OST) and same side (SST) tagging algorithms. The OST tags on the b quark content of a B meson from the same production vertex as the candidate B_s^0, the SST tags according to the s quark content of a kaon produced with the candidate.

DØ uses the di-muon trigger, followed by cut based selection to find 1967$\pm$65 signal events with 2.8fb^{-1} integrated luminosity. The CDF analysis of the same integrated luminosity also uses the di-muon trigger. CDF makes use of a Neural Network (NN) selection procedure to find 3153$\pm$55 signal events.

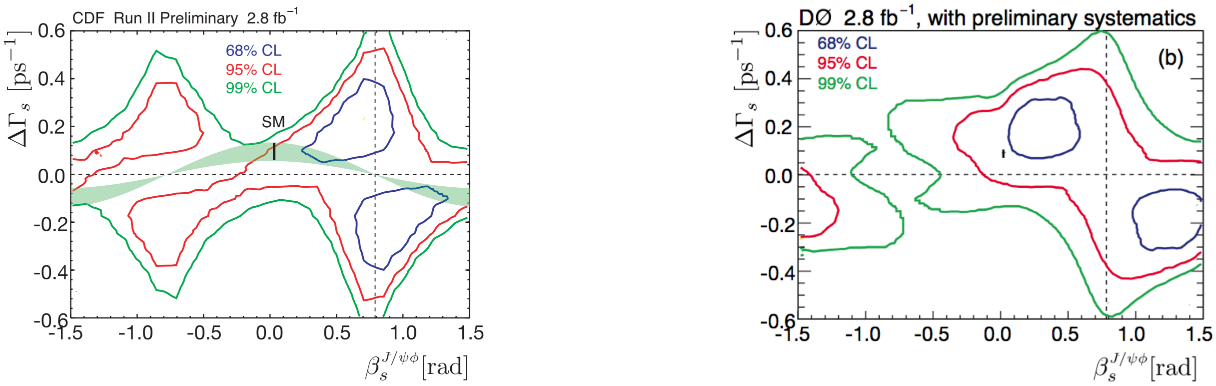

Figure 1: Confidence regions in the $\beta_s^{J/\psi\phi} - \Delta\Gamma_s$ plane, for the CDF analysis (left) and DØ analysis (right). The SM predicted value is marked with a black point.

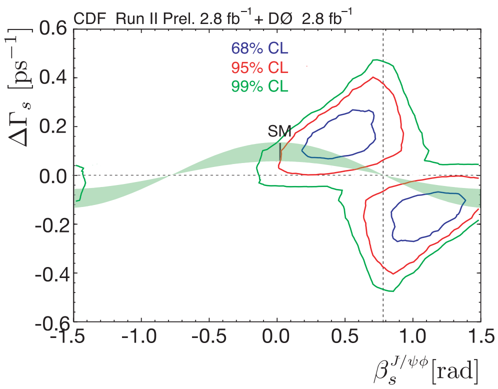

Figure 2: Combined CDF and DØ confidence regions in $\beta_s^{J/\psi\phi} - \Delta\Gamma_s$ plane

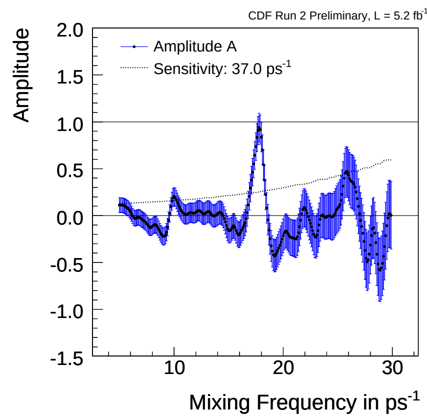

Figure 3: B_s^0 mixing amplitude scan, for calibration of SST

4 Results

In the hypothesis of no CP violation, the CDF experiment presents values of the B_s^0 lifetime, $\tau_s = 1.53 \pm 0.04$ (stat.) $\pm\, 0.01$ (syst.) ps, decay width difference $\Delta\Gamma_s = 0.02 \pm 0.05$ (stat.) $\pm\, 0.01$ (syst.) ps^{-1} and transversity amplitudes, $|A_{\parallel}|^2 = 0.241 \pm 0.019$ (stat.) $\pm\, 0.007$ (syst.) and $|A_0|^2 = 0.508 \pm 0.024$ (stat.) $\pm\, 0.008$ (syst.) using the fit without flavour tagging [4]. The measurements quoted by DØ are in the hypothesis of CP violation, $\tau_s = 1.52 \pm 0.05$ (stat.) $\pm\, 0.01$ (syst.) ps, decay width difference $\Delta\Gamma_s = 0.19 \pm 0.07$ (stat.)$^{+0.02}_{-0.01}$ (syst.) ps^{-1} (with flavour tagging) [5], $|A_{\parallel}|^2 = 0.244 \pm 0.032$ (stat.) $\pm\, 0.014$ (syst.) and $|A_0|^2 = 0.555 \pm 0.027$ (stat.) $\pm\, 0.006$ (syst.) (without flavour tagging) [6].

Figure 1 shows the individual DØ and CDF likelihood contours in $\beta_s - \Delta\Gamma$. With the current data sample it is not possible for either experiment to quote a point value for the phase β_s due to the symmetries in the likelihood function and the non-Gaussian error distribution. Instead the results are presented as frequentist likelihood contours; a profile-likelihood ratio ordering technique is used to ensure full coverage. To make full use of the available statistics, the Tevatron experiments have produced a combined result [7] shown in Figure 2. The p-value for the SM point in the combined analysis is 3.4%, equivalent to a 2.1σ deviation.

5 Upcoming measurements

Both experiments will produce updated analyses in 2010. The DØ experiment will update to a dataset with integrated luminosity of $6.1 fb^{-1}$, and make use of a boosted decision tree

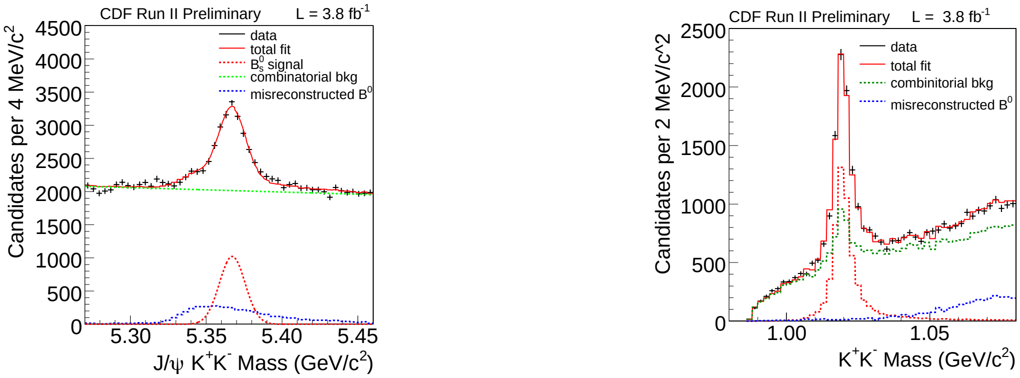

Figure 4: The B_s mass is plotted (left) with a loose ϕ mass cut window, which allows contamination from $B^0 \to J/\psi K^*$ misreconstructed as $B_s^0 \to J/\psi\phi$, this reflection component is fitted with a MC template, the signal B_s mass is fitted with a Gaussian and the combinatorial background with a 1st order polynomial. The invariant KK mass plot(right) is shown with the fractions of each component fixed to that found in the B_s mass fit.

selection to improve the signal to background ratio. CDF plans an update to use 5.2fb^{-1} integrated luminosity, including SST and particle ID for the full data sample, and accounting for contamination of the $B_s^0 \to J/\psi\phi$ signal by $B_s^0 \to J/\psi K^+K^-$ or $B_s^0 \to J/\psi f^0$.

The updated CDF SST is calibrated on a B_s mixing measurement, using the fact that a measured mixing amplitude of ≈ 1 means that the tagger accurately asseses its performance, and an amplitude of > 1 or < 1 implies an under or over estimation of its power, respectively. The amplitude measured for this calibration is $\mathcal{A} = 0.94 \pm 0.15$ (stat.) $\pm$ (syst.), shown in Figure 3. The mixing frequency, $\Delta m_s = 17.79 \pm 0.07$ ps^{-1}, with statistical errors only, is in good agreement with the CDF published measurement.

It has been suggested[8] that a potential contamination of the signal ϕ meson by S-wave f^0 or non-resonant KK of 10-15% could bias the measurement of β_s towards the SM value. The next CDF update includes a full angular analysis of this extra component, however a preliminary study of the invariant KK mass distribution gives no strong indication of a large additional component, as shown in Figure 4.

6 Conclusions

Both of the Fermilab Tevatron experiments have published individual constraints on the CP violating phase $\beta_s^{J/\psi\phi}$ and a combined DØ and CDF result shows a 2σ deviation from the SM prediction. Updated analyses are in progress by both experiments, containing several improvements in addition to the increase from 2.8fb^{-1} to greater than 5fb^{-1} integrated luminosity, including boosted decision tree selection in the DØ analysis, and inclusion of a potential S-wave KK contamination component in the CDF analysis.

References

1. A. S. Dighe, I. Dunietz and R. Fleischer, *Eur. Phys. J. C* **6**, 647 (1999)
2. A.Abulencia et al (CDF collaboration) *Phys. Rev. Lett.* **97**, 242003 (2006)
3. V. Abazov et al (DØ Collaboration) *Phys. Rev. Lett.* **97**, 021802 (2006)
4. The CDF collaboration, Public Note 9458
5. The DØ collaboration, DØ Note 5933-conf
6. V. Abazov et al (DØ Collaboration), arXiv:0810.0037v1
7. http://tevbwg.fnal.gov/results/Summer2009_betas/
8. S.Stone, L.Zhang, arXiv:0812.2832